

Results from impedance reduction in the CERN SPS

single bunch stability

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Fermilab, 9 April, 2002

- Motivation for impedance reduction programme in the SPS
- Identification of dominant impedances
- Results of impedance reduction seen with the beam from
 - single bunch stability
 - beam spectra analysis
- Summary

Work done together with T. Bohl and T. Linnecar (CERN)

CERN SPS:

- $R = 1100$ m, $\gamma_t = 23.2$
- has the PS as injector
- was a $p\bar{p}$ collider (1981 - 1991)
 - 6x6 bunches, $N_b = 10^{11}$
- was an injector for the LEP (1989 - 2000)
 - e^+, e^- (3.5 GeV \rightarrow 22 GeV) from 1987,
8 bunches, $N_b = 2 \times 10^{10}$
- till now is accelerating for fixed target physics
 - p (14 GeV \rightarrow 450 GeV), 4000 bunches,
 $N_b = 10^{10}$
 - ions Pb_{208}^{82+} , total intensity (charges) $\sim 10^{11}$
(sulphur and oxygen in the past)
- will be an injector for LHC (2007)
 - p (26 GeV \rightarrow 450 GeV), 72x4 bunches,
 $N_b = 1.1 \times 10^{11}$
 - ions Pb_{208}^{82+} , probably: Sn_{120}^{50} , Kr_{84}^{36} , Ar_{40}^{18} , O_{16}^8
- will produce beam for CNGS (2005)
 - p (14 GeV \rightarrow 450 GeV), 4000 bunches,
 $N_b = 2 \times 10^{10}$

Motivation for impedance reduction

- Uncontrolled longitudinal emittance blow-up associated with μw signals was observed from 1977 in different operational modes of the SPS:
 - below and above transition
 - with protons and leptons
 - with RF off and on
- Estimations of longitudinal broad-band impedance Z/n scaled to LHC beam parameters suggested (1995) that nominal beam will be unstable at injection in the SPS.
- Different solutions were considered (1996)
 - changing of transition energy in the SPS,
 - more RF cavities in the PS,
 - increasing the injection energy,
 - reduction of impedance of sources of instability
- Continuous emittance blow-up indeed was observed for LHC beam at injection (1999).

Measurements of beam spectra in the SPS

Experimental conditions

- Single bunches at 26, 14, 20 GeV
 - unstable (bunch intensity $5 \times 10^9 - 1 \times 10^{11}$)
 - sufficiently long (20 - 50 ns)
 - with small momentum spread $\pm \Delta p/p$
(more unstable and debunch slowly, $t_d = \tau/(2\eta\Delta p/p)$)
- RF off, but - slow debunching ($t_d \sim 100$ ms)

Methods of data analysis

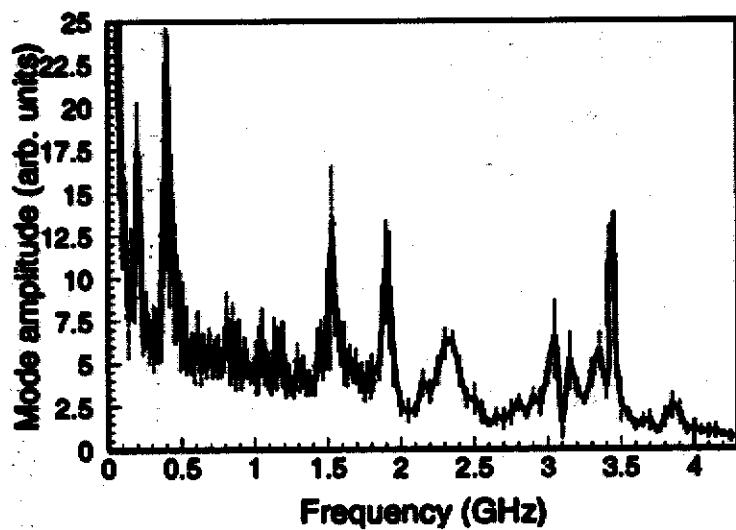
- (I) Measurement of maximum signal at given frequency directly from spectrum analyzer connected to wideband PU (100 MHz - 4 GHz).
- (II) Measurement of bunch profile (the same PU) every n turns with 4 GHz sampling rate followed by Fourier analysis. Restricted to maximum frequency of 2 GHz.

Both use statistics (data from > 10 bunches).

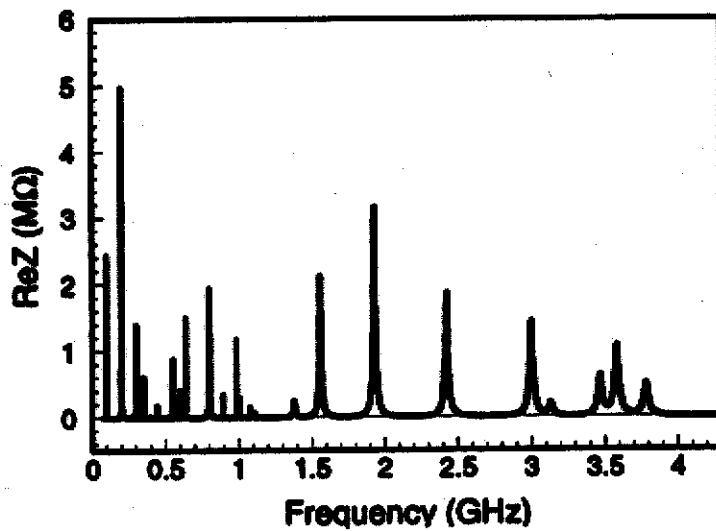
T. Bohl, T. Linnecar, E. S., Phys. Rev. Lett., 1997

Identification of impedance sources (1996)

Spectral distribution measured at 26 GeV



Resonant impedances found



- ✓ Resonant impedances at f_r with high R/Q
- ✓ Peak frequency $\sim f_r$, width $\sim 1/\tau$ (for $1 < \tau f_r < Q$)

• SPS RF system impedance computation & reduction

Longitudinal impedances

• RF systems	total R/Q (kOhm)	Q	operation mode
100 MHz SW	1.4	150	leptons
200 MHz SW	3.87	80	leptons
200 MHz TW	25	130	protons, ions
352 MHz SC	0.93	500	leptons
800 MHz TW	6.5	150	protons

- 400 MHz instability source ?

- Pumping ports (~1000):

high frequency signals (1.5 GHz, 1.9 GHz, 2.4 GHz...)

total R/Q = (25 - 45) kOhm, Q~ 50.

→ SPS impedance reduction programme under project SLI: SPS as LHC injector

Possible 400 MHz band sources in the SPS (1996)

$f_r = 400 \text{ MHz}$ for $TM_{010} \rightarrow r = 28 \text{ cm}$

n	Element	No.
1	400SC, LHC prototype cavity	1
2	MSE, extraction septum	10
	MST, extraction septum, thin	6
	TPST,TPSS, protective shield	2
	MSL, lepton injection	2
3	MKA antiproton injection	2
	MKDH H dump sweep	3
	MKD V dump sweep	2
	MKE extraction	3
	MKLE electron extraction	1
	MKLP positron extraction	1
	MKP proton injection	3
	MKQH H q measurement	1
	MKQV V q measurement	1
4	ZS electrostatic septum	10
	TCE extraction collimator	2

SPS impedance reduction programme

MSE and MST septa shielding

year	shielded	unshielded
1997	0	16
1998	1 MSE	15
1999	3 MST + 5 MSE	8
2000	6 MST + 10 MSE	0

F. Caspers, B. Goddard, A. Rizzo

Measurements with the beam

1999: no visible changes

2000: small increase of the threshold, but instability is still there...

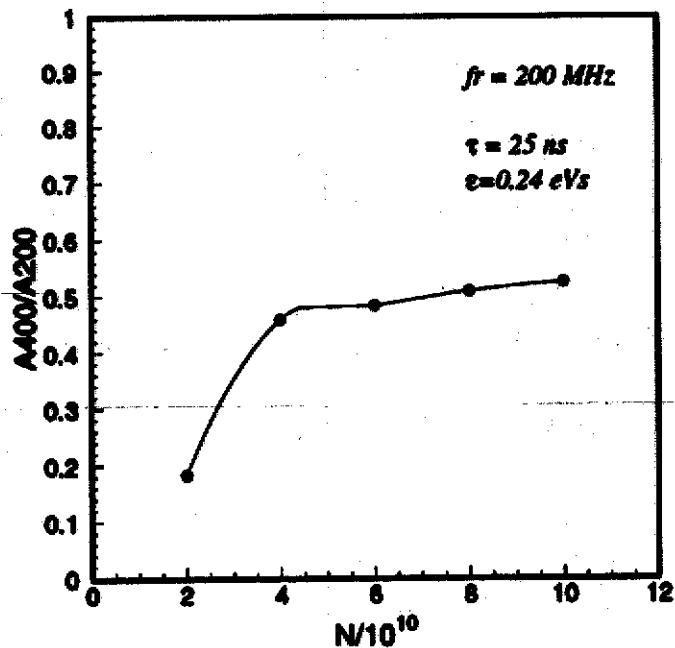
January 2001, LHC Workshop Chamonix XI:

400 MHz impedance - where are we?

400 MHz signal as a second harmonic

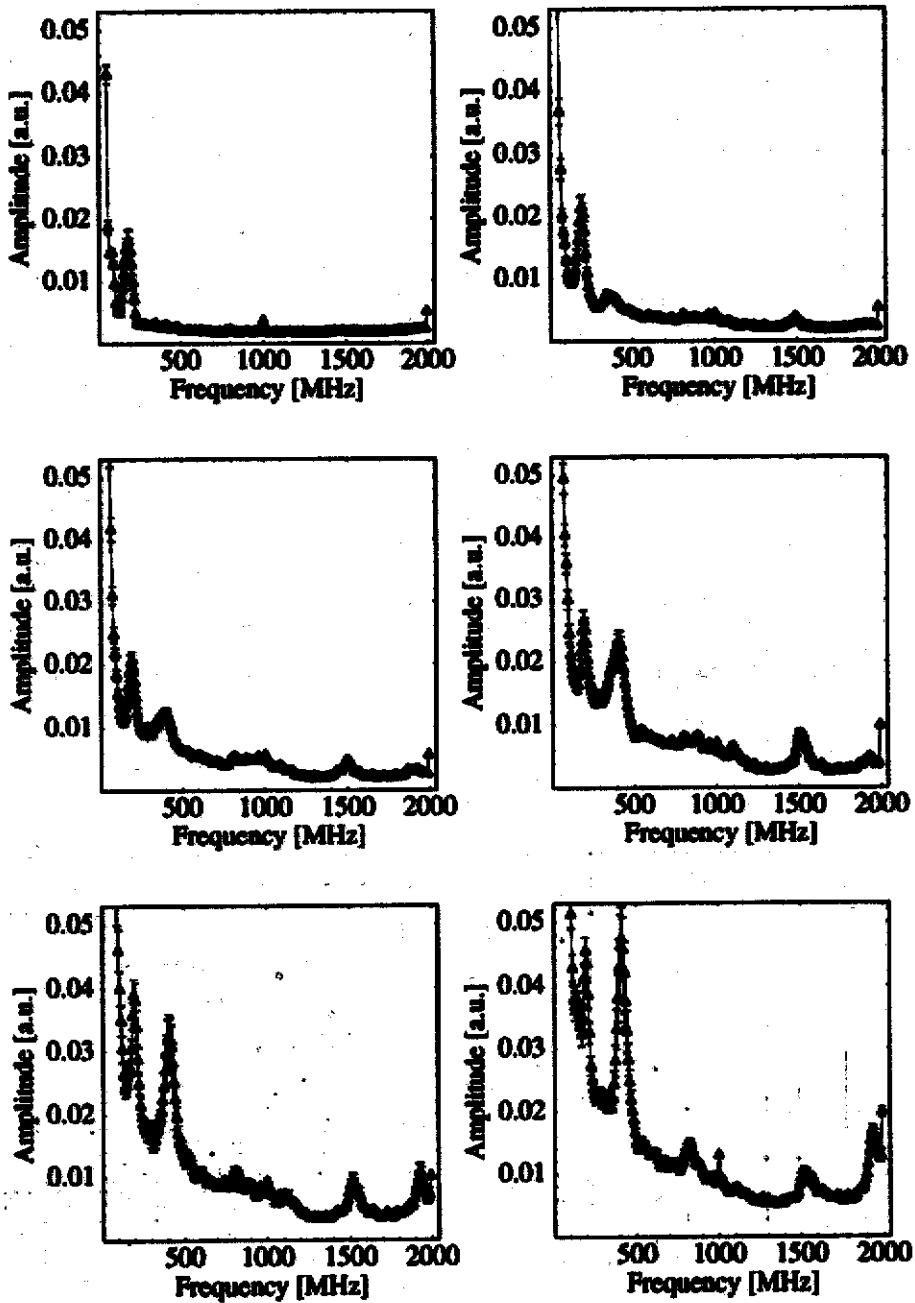
There will always be some signal at 400 MHz due to the presence of the 200 MHz TW RF system and nonlinearity of the process

Relative amplitude of the signal at 400 MHz as a function of bunch intensity (ESME simulations)



✓ For the second harmonic: amplitude ratio
 $A_{400}/A_{200} < 0.5$

The Fourier spectra for different bunch intensities (1999)

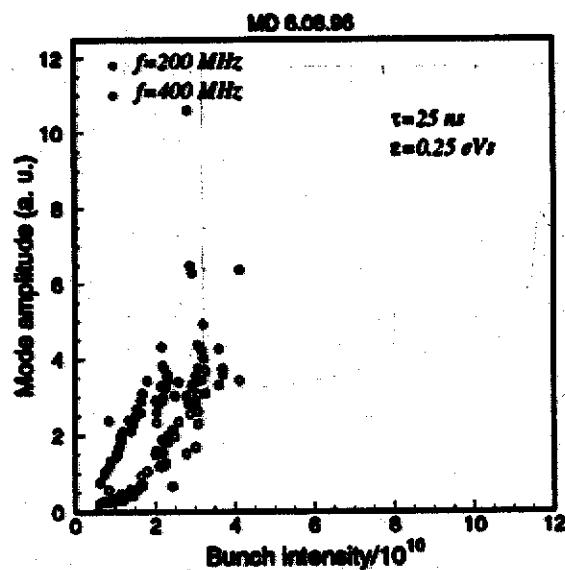


Averaged over ~ 15 acquisitions for bunches with
 $N/10^{10} = 1.8, 2.4, 3.0, 3.8, 4.6, 5.7$ (from top left)

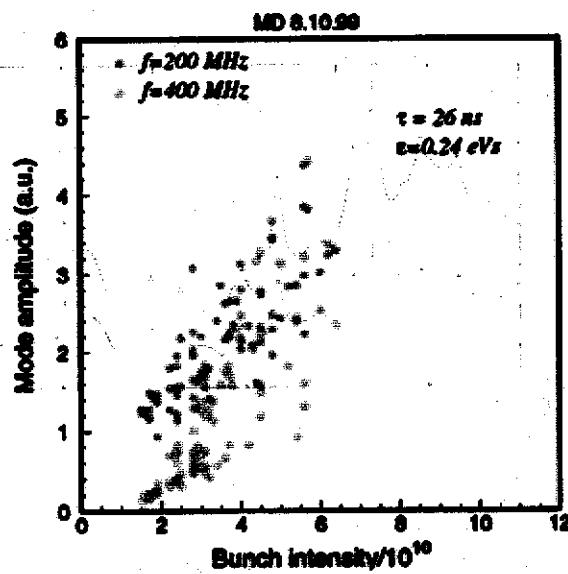
✓ Relative amplitude of signals depends on intensity

Mode amplitude at 200 and 400 MHz as a function of intensity and bunch length

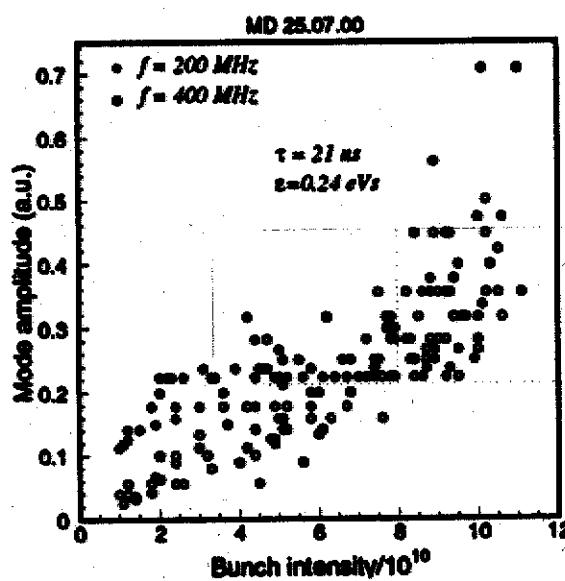
1996



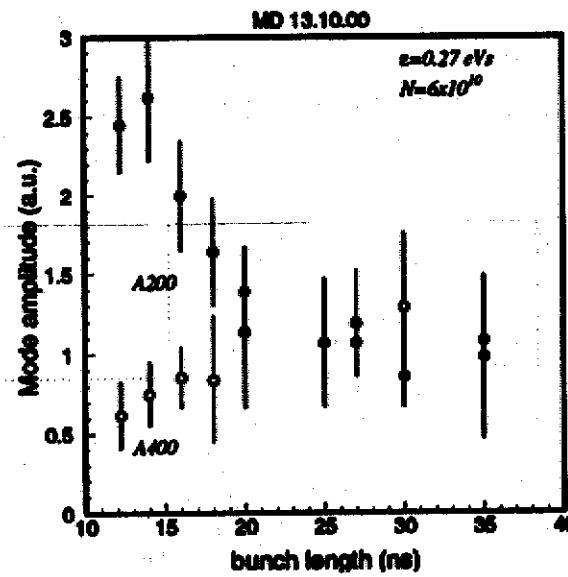
1999



2000



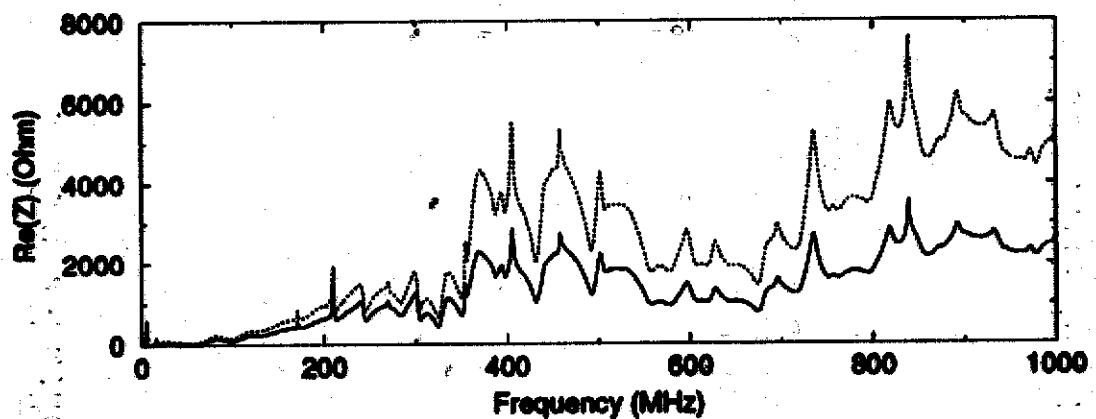
2000



✓ Above some intensity $A_{400} \geq A_{200}$!

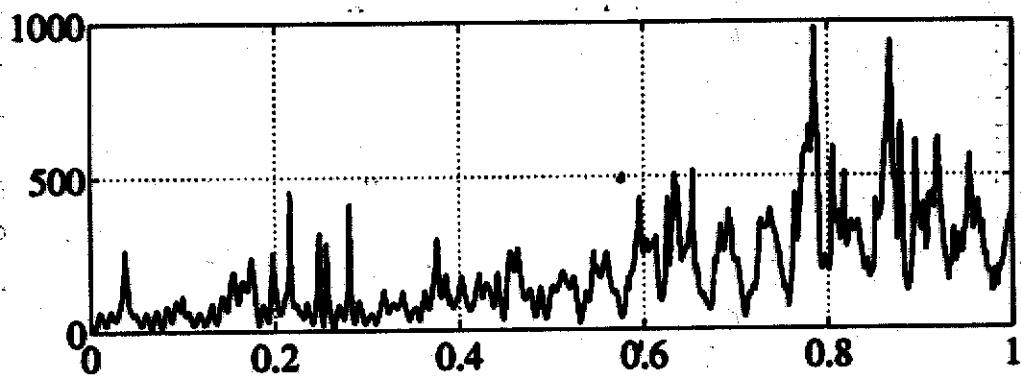
400 MHz band sources - measurements by wire method

MKE kicker impedance



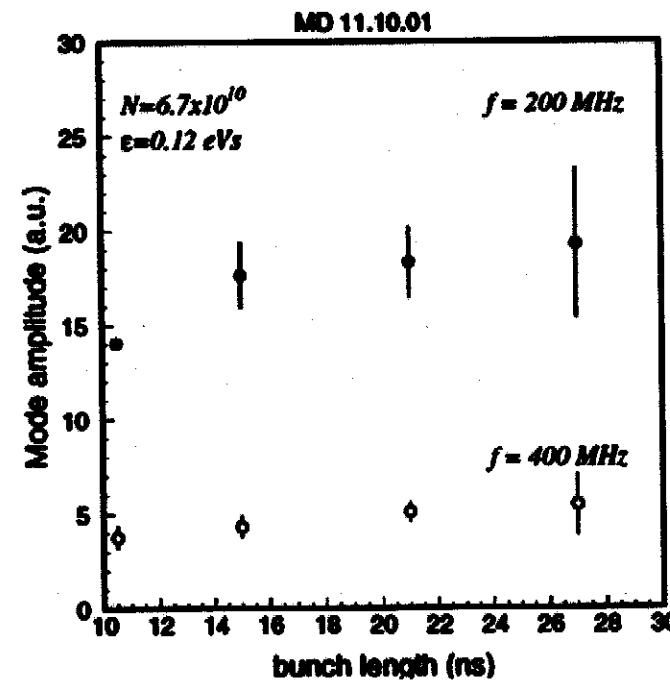
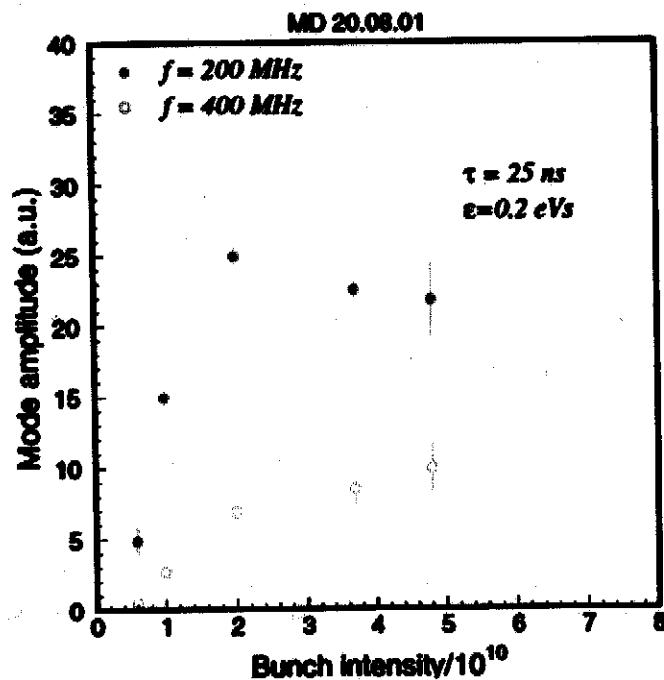
F. Caspers, C. Gonzalez, M. D'yachkov, E. S., H. Tsutsui, 2000

Impedance of electrostatic septum ZS - $\text{Re}[Z]$ (Ohm)



F. Caspers, T. Linnecar, A. Mostacci, E. S., 2001.

Plasma mode amplitudes (10^10 a.u.)
200 MHz and 400 MHz mode amplitudes in 2001

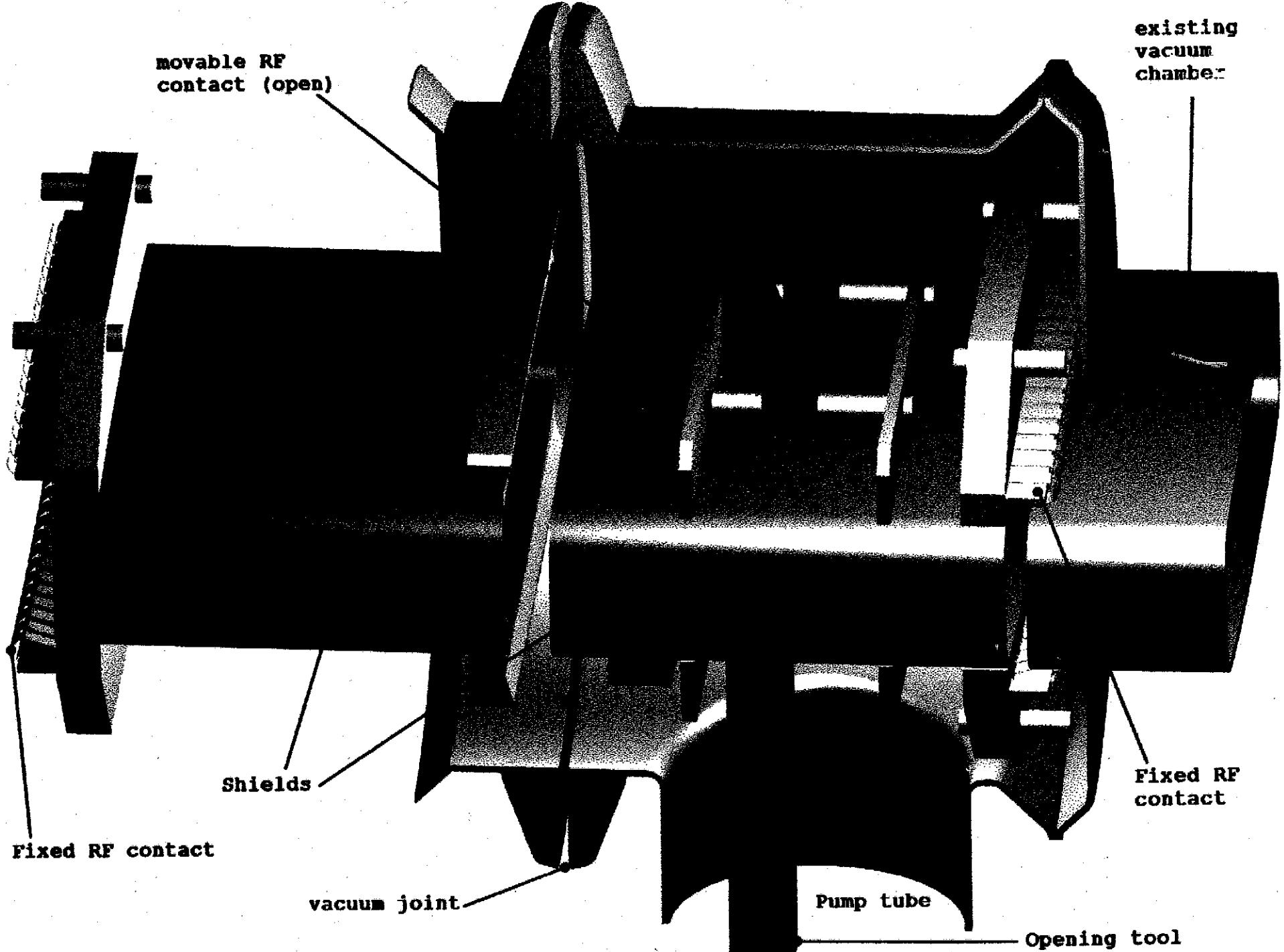


✓ Now: amplitude ratio $A_{400}/A_{200} < 0.5 \rightarrow$ second harmonic of 200 MHz signal.

Pumping ports (1000!)

- 97% of them were shielded (shutdown 2000/2001).
- Design of shield:
 - good RF screening - while still pumping!
 - sliding electrical contacts, which allow magnets to be displaced when necessary.
- During 5 months 400 main dipole magnets were displaced to install 2400 sub-assemblies of 30 different screen models. Complete re-alignment of the SPS afterwards.

Project coordinators: P. Collier and A. Spinks



Reference measurements at 26 GeV in 1999 - 2001

Longitudinal plane

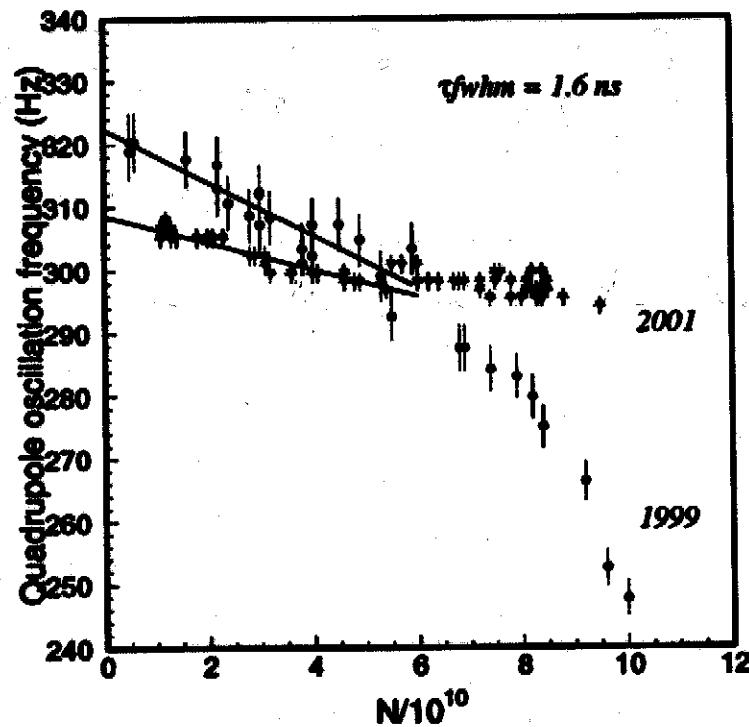
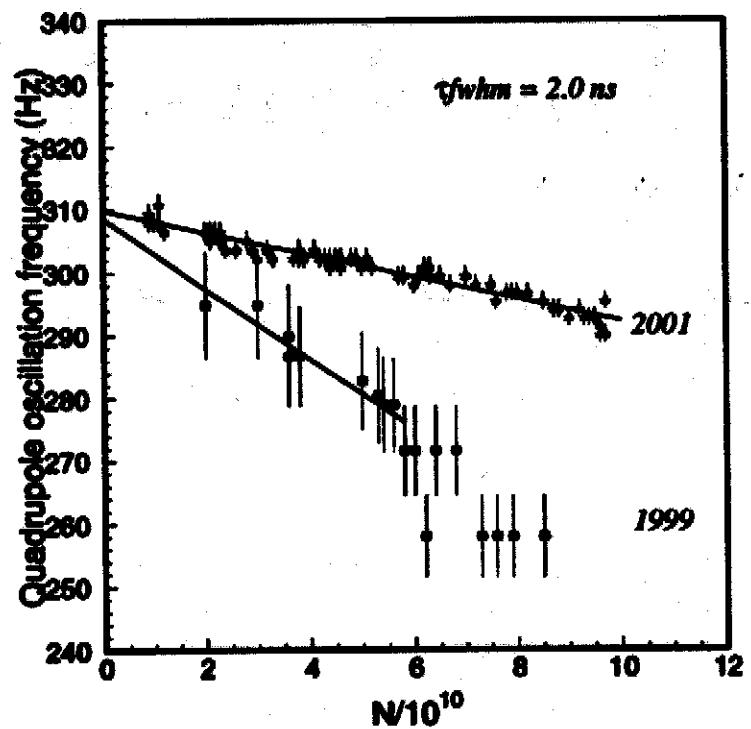
- With RF on - to see global effect on bunch stability
 - Quadrupole frequency shift with intensity
 - Bunch length as a function of intensity
- With RF off - to monitor changes of impedance at particular frequencies
 - Bunch spectra

Transverse plane

- Coherent frequency shifts with intensity

H. Burkhardt, G. Rumolo, F. Zimmermann

Quadrupole oscillation frequency as a function of bunch intensity before and after impedance reduction



26 GeV, 200 MHz RF system, voltage 900 kV

Quadrupole frequency shift

The linear shift of quadrupole frequency with intensity N

$$f_{2s}(N) = a_i - b_i N \times 10^{-10},$$

where $a_i = f_{2s}(0)$ and $i = 1, 2$ are two measurement methods.

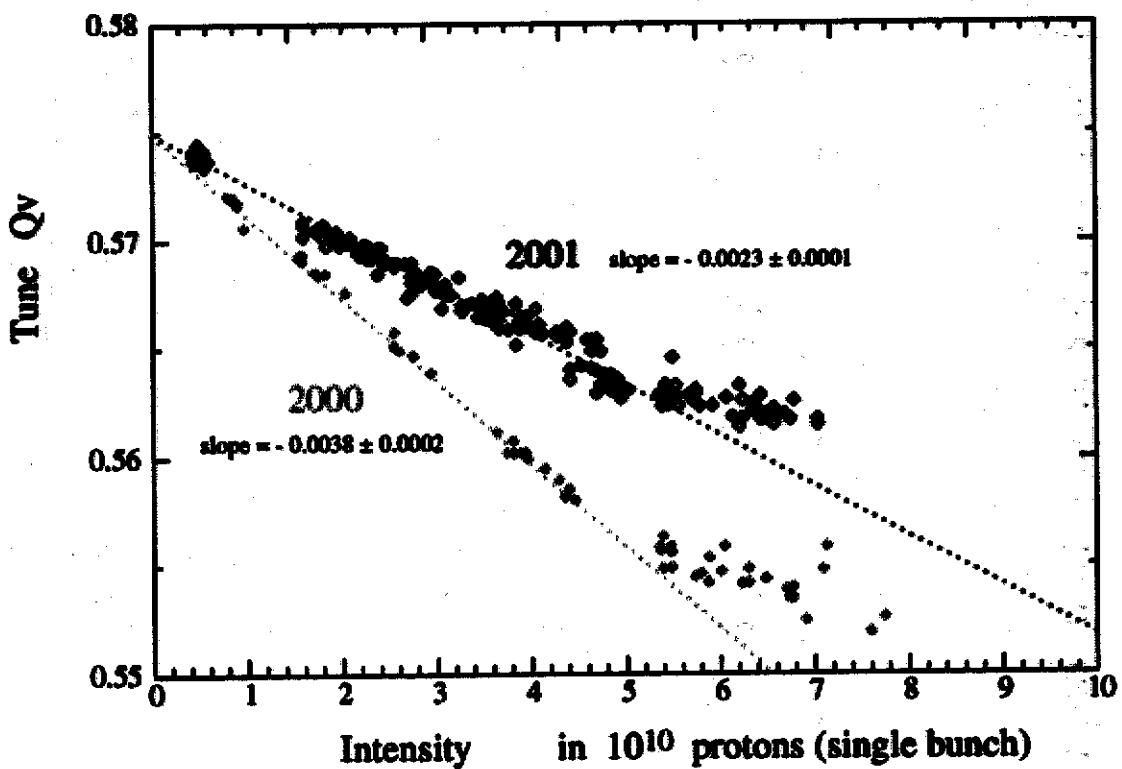
Results of measurements

Run	Date	$\bar{\tau}_{FWHM}$ ns	ε (PS) eVs	a_1 Hz	b_1 Hz	a_2 Hz	b_2 Hz
1	15.11.99	1.87	0.25	308.6	5.6		
2	25.11.99	1.63	0.15	322.4	4.2	323.0	4.2
3	07.08.01	2.01	0.16	309.9	1.8	308.3	1.6
4	07.08.01	1.56	0.15	306.1	2.1	307.9	1.7

On average factor 2.5 reduction in $b \propto Z/n$.

Reference measurements in transverse plane

Vertical coherent tune shift

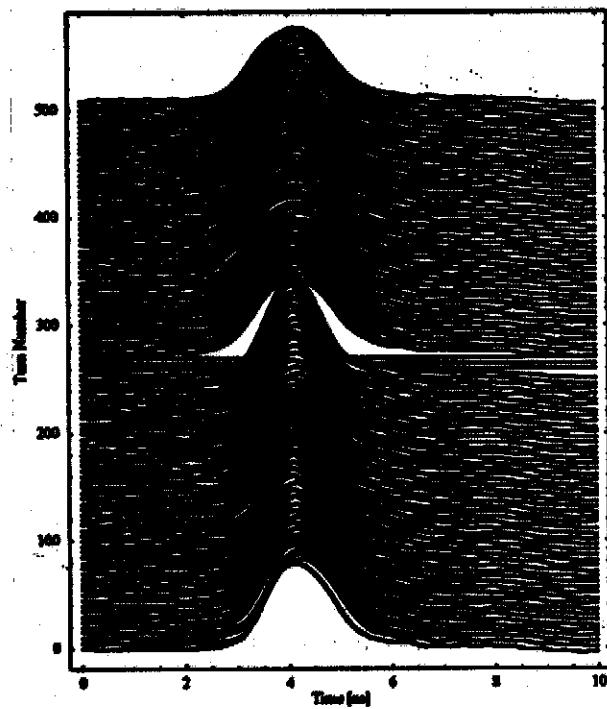


Slope ratio: $0.023/0.038 = 0.6 \longrightarrow 40\% \text{ reduction}$

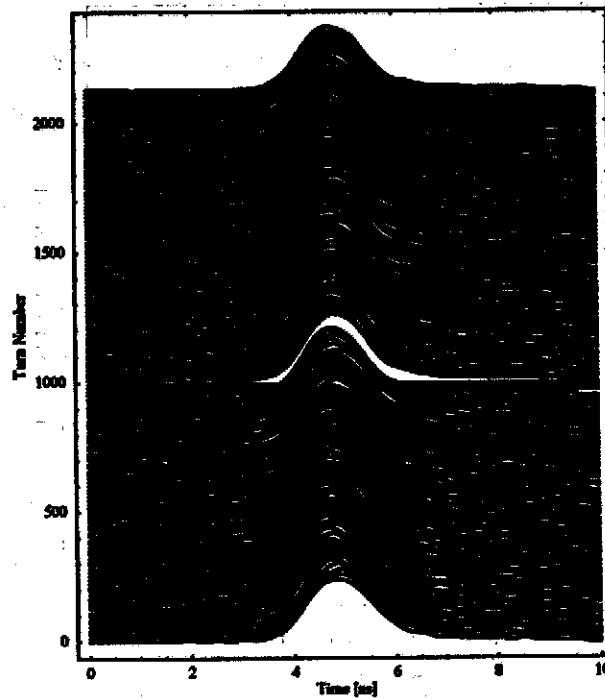
H. Burkhardt, G. Rumolo, F. Zimmermann

Bunch profiles at injection and 600 ms later

1999



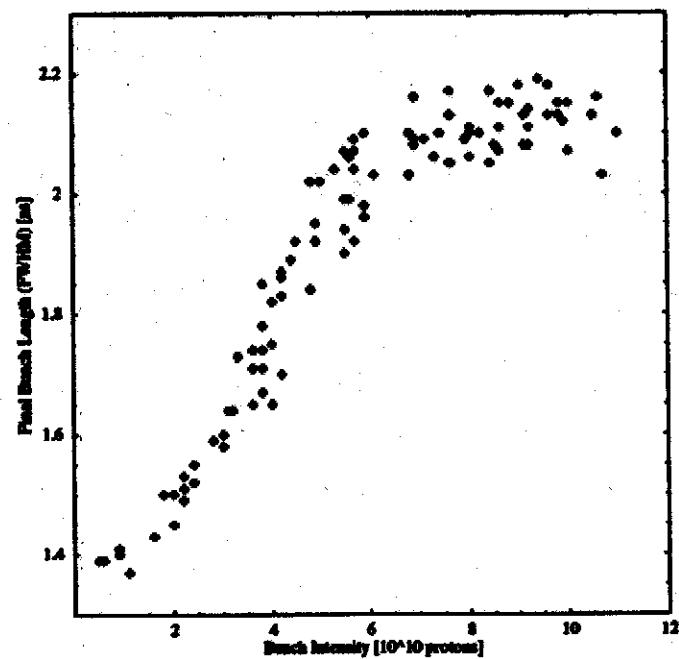
2001



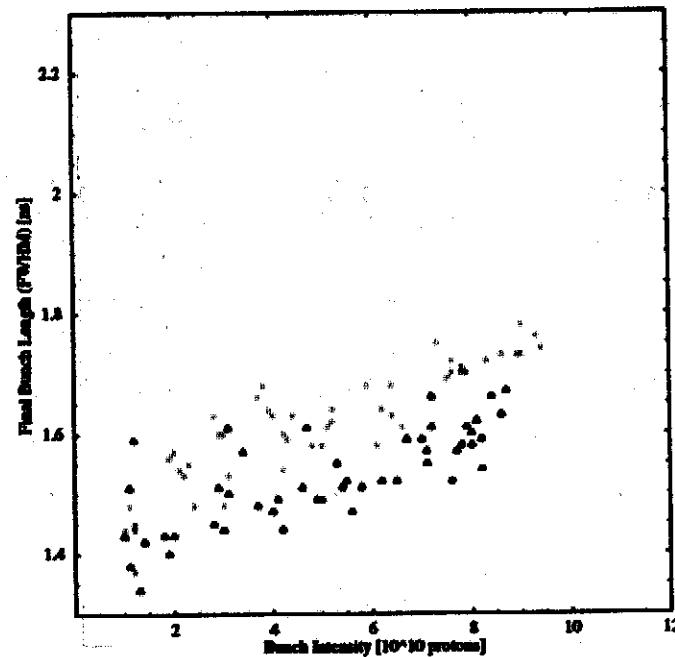
Initial bunch length: $\tau_{FWHM} = 1.6$ ns, intensity $N = 4.2 \times 10^{10}$

Bunch length (FWHM) at 600 ms after injection as a function of intensity

1999



2001



$$\tau_{FWHM} = 1.6 \text{ ns}$$

$$\tau_{FWHM} = 1.6 \text{ and } 2 \text{ ns}$$

- ✓ Difference in the slope \sim factor 7
- ✓ Measurements in 1999 were done above μw instability threshold

Low frequency inductive part Z/n of different elements (1999):

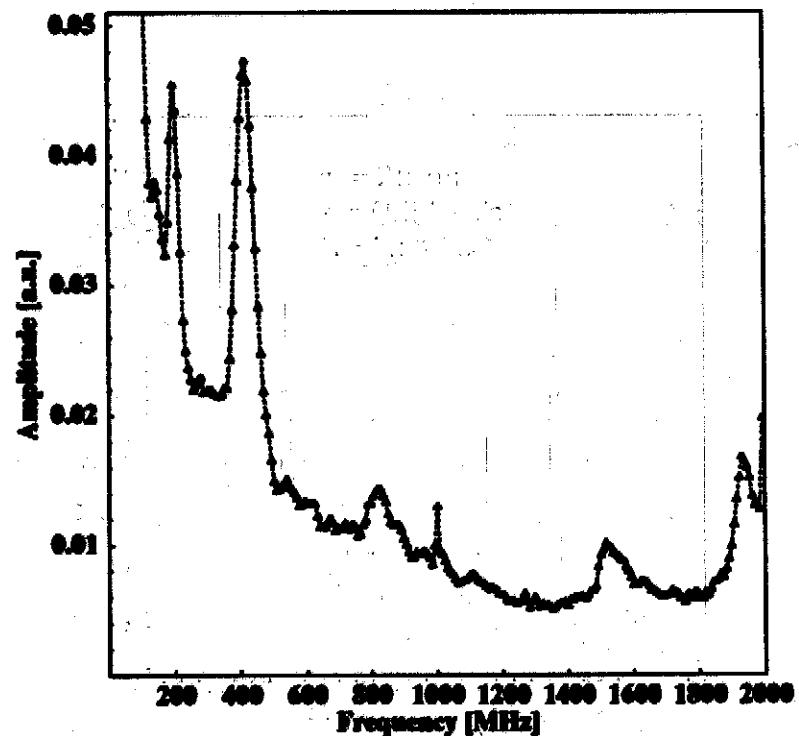
Element	N	$\Im[Z]/n$ Ohm	Source of information	Reference
TW200-F cavities	4	4.9	calcul.	G.Dome
TW200-HOM	4	0.25		
TW800-F cavities	2	0.35	calcul.	G.Dome et al
Lepton RF cavities	28	1.7	cal. + meas.	many different
Vacuum ports	900	3.0	calcul.	W.Hofle et al
MKE + MKP kickers	6	2.0	cal. + meas.	F.Caspers et al
MSE + MST septa	8	0.1	calcul.	T.Linnecar et al
Bellows	900	0.1	calcul.	L.Vos
Total reduction		6.8		

Space charge: at 26 GeV, LHC beam $\Im[Z]/n \sim -1$ Ohm

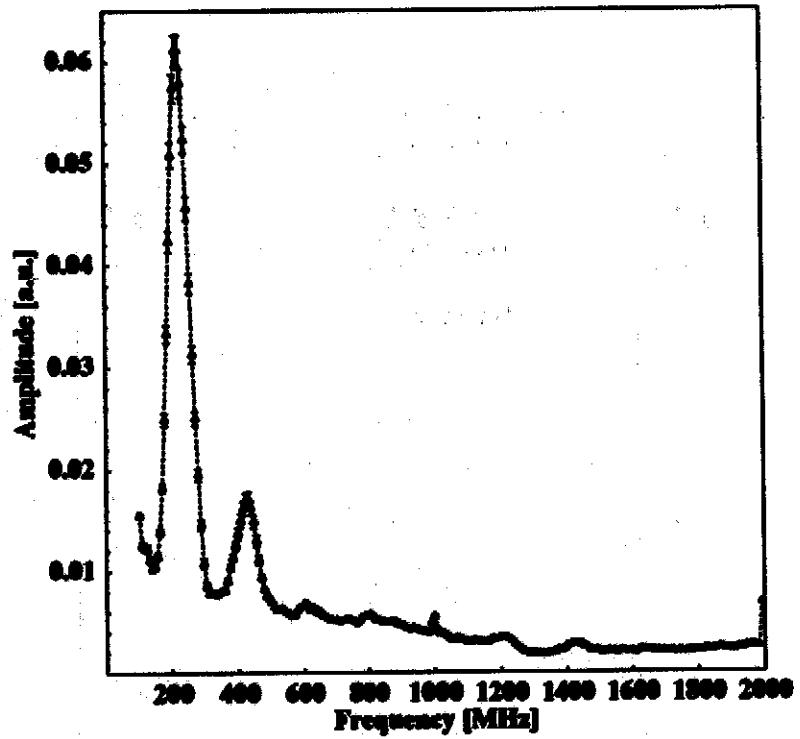
Measurements with the beam: $\Im[Z]/n = (10 - 20)$ Ohm

Average projections of Fourier spectra up to 2 GHz

1999



2001



$$N = 5.7 \times 10^{10}$$

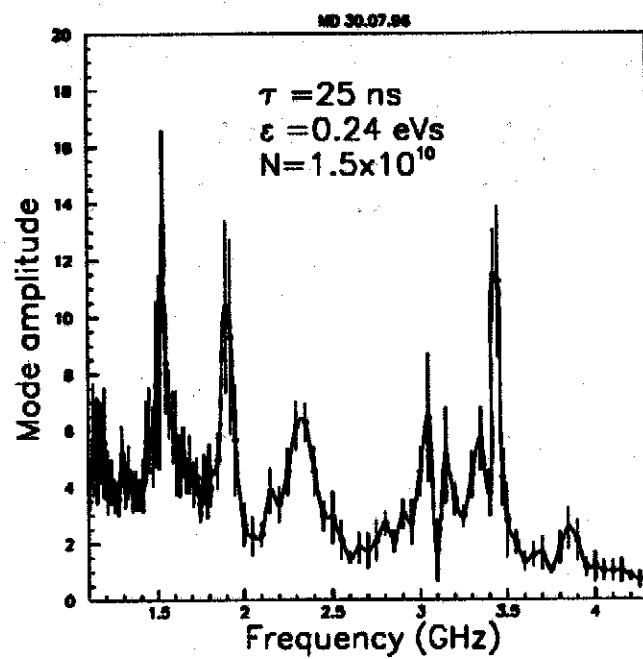
$$\epsilon = 0.24 \text{ eVs}, \tau = 25 \text{ ns}$$

$$N = 6.0 \times 10^{10}$$

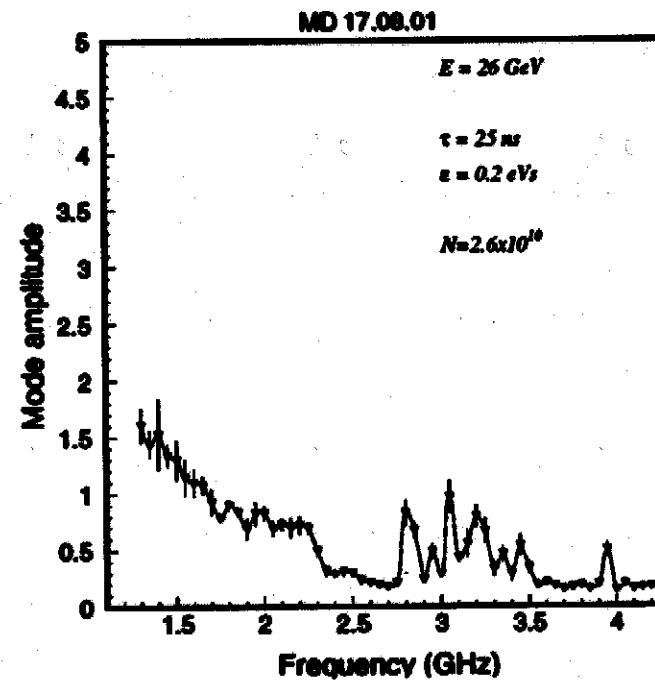
$$\epsilon = 0.2 \text{ eVs}, \tau = 25 \text{ ns}$$

The mode amplitude scan at high frequencies

1996



2001



- ✓ Signals at 1.5, 1.9 and 2.4 GHz due to pumping ports are no longer there
- ✓ Pick-up cut-off frequency is 2.8 GHz

Summary

- **Studies of microwave instability with different beam and machine parameters have helped to identify the dominant longitudinal impedances in the SPS.**
- **As a result of the recent impedance reduction programme the stability of a single bunch in the SPS is significantly improved.**
- **Efficient shielding of pumping ports is confirmed by the absence of high frequency signals in the beam spectra measurements of 2001. The screening and removal of MKE and MKP kickers led to the disappearance of the instability at 400 MHz.**
- **The microwave instability is not observed in the bunch length measurements of 2001 (intensities up to 10^{11} p/bunch, $\epsilon = 0.15$ eVs) —> nominal and possibly ultimate LHC bunch is stable at 26 GeV ($\epsilon = 0.35$ eVs).**
- **The life time of LHC beam at 26 GeV in the SPS has significantly increased in 2001 and no losses were observed.**
- **The present SPS performance limitations are coupled-bunch instabilities and the e-cloud effect.**